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Article

35 Years of Ground-Based Gamma-ray Astronomy

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Abstract: This paper provides a brief, personal account of the development of ground-based gamma-ray astronomy, primarily over the last 35 years, with some digressions into the earlier history of the field. Ideas related to the imaging of Cherenkov events and the potential for the use of arrays were in existence for some time before the technical expertise required for their exploitation emerged. There has been occasional controversy, great creativity and some heroic determination—all of it part of establishing a new window into the universe.

Keywords: gamma-ray astronomy; astroparticle physics; Cherenkov telescopes

1. Introduction

It came as something of a surprise to be asked to write this review article, until I realised that I have indeed been working in the field of ground-based gamma-ray astronomy for over 35 years, having started my PhD in Durham with Ted Turver in 1984. I have never managed to leave Durham (at least not for long), which either shows a singular lack of imagination or great dedication to the cause. While I may not have gone anywhere, ground-based gamma-ray astronomy certainly has, and this article is an attempt to give an overview of that progress from a very particular position in a small city in the far north-east of England. Others have written much more comprehensive overviews of the development of ground-based gamma-ray astronomy than I could ever hope to [1,2]. This is therefore a personal view, and I cannot claim that it is completely impartial or indeed complete at all.

2. The 1980s—Hunting the Snark

As I started my PhD, the telescopes that Durham operated at the Dugway Proving Grounds in Utah, USA, had just shut down. Sundry parts arrived shortly thereafter in a couple of shipping containers, and the group got on with salvaging the useful equipment—primarily, a great deal of NIM electronics and some 5-inch and 3-inch diameter photomultiplier tubes (PMTs). There were 4 telescopes in the array at Dugway, known as the Mark I telescopes. One of these was replaced by a Mark II telescope, so it was 3 Mark I instruments and one Mark II telescope that came back to Durham in 1984. It is worth considering how those telescopes came about, as it explains much of the direction of Durham's work at the time.

The starting point is a paper published by Turver and Weekes in 1978 [3]. In it, they described some simulations that they had performed of Cherenkov light from gamma-ray and proton-initiated airshowers. To our eyes now, the number of simulations seems extremely small (there are never more than 100 simulations at a given energy and sometimes as few as 9), but bearing in mind the computing facilities available at the time, this represented a considerable effort. The proposal they made for a Cherenkov telescope system sounds familiar to us now:

Two large reflectors of size and optical quality similar to the 10 m detector¹ would be operated in parallel with a lateral spacing of about 100 m. Each reflector would have a matrix of 5 cm phototubes (19 or 37 in each), each tube having a field of view of 0.25° half-angle. The system would be triggered by a coincidence between one or more detectors in each reflector; the pulse heights of all the tube outputs



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would then be recorded digitally (6 bit accuracy), so that two “images” would be obtained of the angular distribution of the shower light with 0.5° resolution. By analysis of the “images” in the two systems, it will be possible to determine the energy and the angle of incidence of the shower to high precision.

Although the prospect of using the differences in the airshowers to separate the gamma-rays from the overwhelming background of hadron events had been postulated some time ago by Jelley and Porter [4], this represented a considerable step forward from the state-of-the art in 1978—when even the Whipple reflector had only a single 5-inch (12.5 cm) PMT at its focus. Even more, at a Royal Society meeting in 1981, a plan for the future was developed [5]. This included an outline of what they described as a ‘third generation’ experiment that would use both timing and imaging techniques (Figure 1). There is also a list of potential sources in the paper; while they were not so lucky with the Galactic objects (although, of course, the Crab Nebula was included), the short extragalactic target list included Centaurus A, M87 and BL Lac, all of which are now known to be VHE (very high energy) gamma-ray emitters.

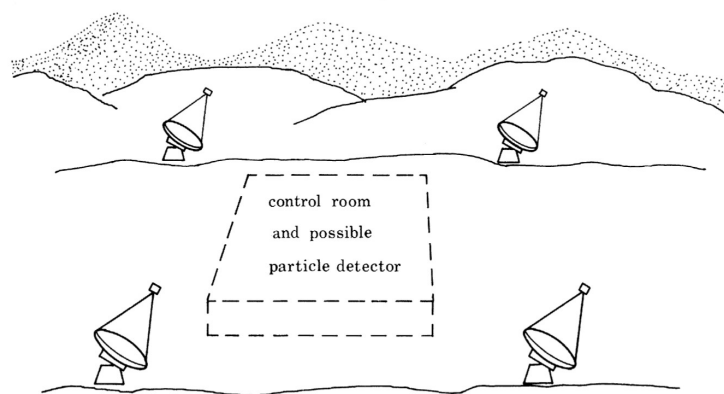


Figure 1. The ‘third generation’ gamma-ray telescope array proposed by Turver and Weekes [5]. The suggested energy range was 10 GeV to 10 TeV; each reflector would be 10–15 m in diameter and be separated by 50–100 m.

To build more than one large, sophisticated telescope was beyond any one group’s budget. The Whipple team built the first multi-PMT camera, while Durham went on to experiment with the array concept, but without any imaging capability, hence the 4 Dugway telescopes. I suspect (though this is before even my time) that financial constraints played a part on this. One can only speculate as to what might have happened had the two approaches been brought together earlier.

The individual Durham telescopes (Figure 2) each consisted of three reflectors, with a PMT acting as the detector for each reflector. The 3 PMTs were operated in coincidence, as a way of reducing the noise in the system. In particular, this removed events produced by muons passing through the detectors from the datastream. There was no array trigger, but events common to more than one telescope were identified offline using event timestamps. ‘Absolute’ time was provided by a central crystal oscillator; this oscillator slowly drifted from the correct time, so it required regular resetting from a radio signal. The drift rate was not always the same—presumably due to differences in the ambient temperature—so it was monitored regularly and only reset when required, because the discontinuities caused by the resets were a nuisance when it came to the data analysis. Nonetheless, roughly monthly resets were required, and a large, hand-written piece of card with the characteristics of the clock drift for each reset was pinned to a door in the observatory in Durham for reference when analysing data.



Figure 2. One of the Durham Mark I telescopes situated at Dugway Proving Ground, Utah in the USA.

The Mark I telescope mirrors were army-surplus searchlight mirrors, much like the mirror used by Jelley and Galbraith for the first atmospheric Cherenkov detector [6], but larger (1.5 m diameter). The optics were not ideal, so they were improved by the use of a secondary Cassegrain mirror system—dual-mirror Cherenkov telescopes are not so new after all. The Mark II telescope departed from this design; there were still three reflectors, but each consisted of seven custom-built mirrors with more suitable 250 cm focal lengths made from machined and polished aluminium. A 3-inch (7.5 cm) PMT was placed at the focus of each reflector.

2.1. Telescopes Everywhere

In August 1986, a NATO Advanced Research Workshop devoted to VHE Gamma Ray Astronomy was held in Durham. This provides a useful survey of the field at the time, and I briefly consider the science results in Section 2.3. There were many Cherenkov systems dotted around the world; some were similar to Durham's, with multiple individual reflectors on a single mount, such as the Haleakala telescope in Hawaii, with its 6 reflectors, and the array of 3 triple-reflector telescopes at Potchefstroom in South Africa. In Pachmarhi in India, there were 18 individual telescopes, 10 with 0.9 m diameter mirrors and 8 with 1.5 m diameter mirrors, each on their own mount. The largest single array in terms of mirror area was at Themis in France, where there were 7 telescopes, each 7 m in diameter. The University of Adelaide had telescopes both at White Sands (3 single-reflector telescopes of 5 m diameter) and a triple-reflector telescope in Woomera. Finally, the Whipple Observatory was in the process of adding a second telescope to the first to create HERCULES² [7]. The ideas that HERCULES was designed to exploit would eventually have profound effects.

2.2. The Durham Mark III Telescope

The workshop in 1986 marked, for Durham, the end of the construction phase of the Mark III telescope. Ted Turver and Keith Orford had recognised that the southern hemisphere would be, in all likelihood, a good hunting ground for gamma-ray astronomy, so the telescope was built on the old Sydney University Giant Airshower Recorder (SUGAR) site, near the small town of Narrabri in Australia. Like the Mark II telescope, the Mark III had three reflectors consisting of multiple individual mirrors on a single mount (Figure 3). In this case, the three 'cameras' consisted of 750 mm diameter PMTs arranged in a hexagonal pattern. As before, the time reference was provided by a local oscillator cross-checked with a radio signal. However, by now, we were using a rubidium oscillator (seen in Figure 4),

which was much better than the crystal that had been used in Dugway. It required resetting to the Royal Australian Navy signal only rarely.

Details of the Mark III can be found in [8]; I will just mention a few important or unusual features here.

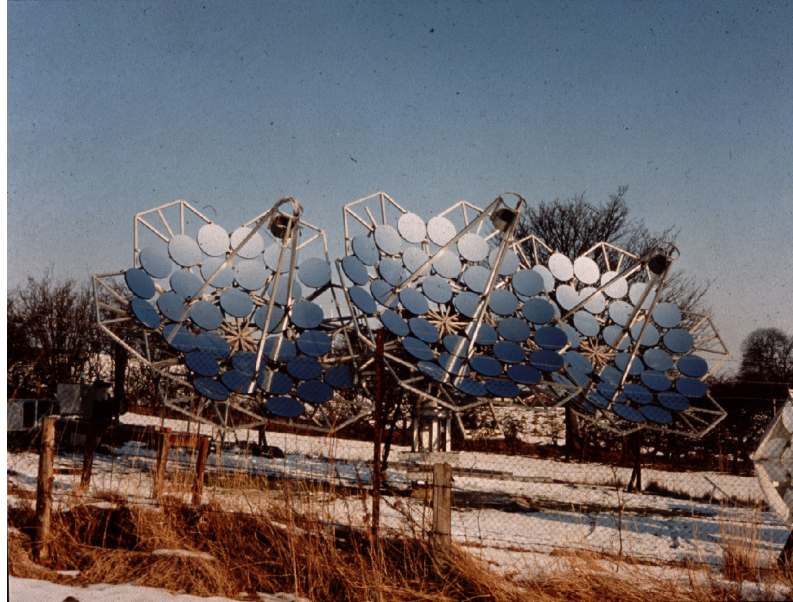


Figure 3. The Durham Mark III telescope under construction in Durham, with about 75% of the mirrors in situ. Note the snow on the ground! It is also possible to see the edge of the Mark II telescope at the bottom right, which was rebuilt in Durham for test purposes.



Figure 4. The Durham Mark III telescope control room. While the main DAQ was performed by a Motorola 68000 computer situated under the console, the system's interfaces were all BBC microcomputers. These were remarkable- and remarkably cheap-computers for their time. The copper box on top of the console contains the rubidium oscillator used for timing.

2.2.1. Automatic Gain Control

Before imaging existed, there were a number of observing techniques employed in the hope of detecting a signal. Tracking an object of interest was obviously possible, but did not provide a good means of detecting a source that did not have a time-varying flux.

The simplest technique was ‘drift scanning’, in which the telescope was kept at a fixed position, and the object of interest was allowed to pass through the telescope field-of-view. A source would then be identified by the rise in count-rate as it passed through the field-of-view. This was the only method that could be used for extended objects, such as the Galactic plane, in small field-of-view instruments. The final method, and the one most often used with the Mark III, was ‘chopping’. Here, the central PMT and the off-axis PMT in the same horizontal plane were alternately pointed at the source—in the Mark III’s case, the ON/OFF switch was made every 15 min. This allowed for the study of both constant and time-varying objects.

The problem with all these techniques was that PMT gain could change by as much as 10%, going from dark to bright fields, resulting in a change in count-rate of a few percent. This was of the same order as an (optimistically!) expected signal. The answer was to stabilise the PMT gain by using the light from a green LED (blue LEDs were not available in the 1980s) embedded into a perspex ring placed around the PMT entrance window, thus distributing light across the PMT. The LED current was controlled via a feedback loop which kept the anode current constant at the 1% level. This system, known by us in Durham as automatic gain control, and by the Whipple folks as padding lamps, effectively removed short-term variations caused by changes in night-sky background or atmospheric conditions. The drawback was that this introduced extra noise into the system, although a suitable coincidence requirement mitigated this.

2.2.2. Aluminium Surface, Honeycomb Mirrors

The Mark III telescope was equipped with lightweight mirrors, made using a construction technique based on that of the antenna sections of the UK/NL millimetre-wave telescope which the staff at the Rutherford Appleton Laboratory had built. The reflective material, made by Alanod³, was (and still is) designed for home interiors and lighting, now increasingly for solar power. It wasn’t clear how it would perform outside for our purposes, so samples were sent to Trevor Weekes at Whipple to put in the test system there. A letter with the results (no e-mails then) came back some time later with the comment “It’s very good—what is it?”. This was used for the 120, 60 cm diameter mirrors needed for the Mark III telescope.

Each mirror surface was formed around a mould under vacuum and bonded to aluminium honeycomb (used for aircraft construction) which had been crushed to approximately the correct profile. The back of this was bonded to a flat backplate and the whole mirror was encircled by an aluminium ring to provide structural integrity. The reflectance was reasonably good—over 75% between 300 and 500 nm—and the image of a point source was around 10 mm in diameter, which corresponded to about 0.2° , more than adequate for a telescope in which the field-of-view of each PMT was 1° .

These mirrors were cheap, lightweight, and turned out to be durable (particularly when tools were inadvertently dropped on them). However, one drawback was that on cold, damp, winter nights, condensation would form on the mirrors. A number of approaches were tried to obviate this, including heating the mirrors, which would have needed 120 kW for the whole telescope, and was quickly abandoned. The best approach was to spray the mirrors before observing with a solution of what was called ‘high quality wetting agent’ in any papers on the subject. It was, in fact, dishwasher rinse aid, purchased in quantity from the supermarket in Narrabri. Heaven knows how their stock control system coped with the apparently huge fluctuation in the washing of dishes in the area between summer and winter. If it was particularly cold and damp, condensation would start to form anyway, happily usually just as observations were finishing for the night. The result the next morning was sparkling clean mirrors.

At the time, it was thought that the condensation was due to the honeycomb structure of the mirrors. We now know that the main reason for condensation on mirrors is high emissivity of the reflective surface in the infrared, which causes them to cool rapidly when pointed to the cold night sky, so that when the relative humidity is high, the mirror

temperature is soon below the dewpoint [9]. A similar composite structure employing aluminium-coated glass reflective surfaces has, of course, proved rather successful.

2.2.3. Signal Enhancement

Although imaging was not possible with the Mark III telescope, the hexagonal geometry of the detector package did allow for some basic background reduction to be attempted. The assumption was that all the gamma-ray events from the object being tracked would be contained within the 1° field-of-view of the central PMT. The centres of the outer PMTs were 2° from the middle of the central PMT; thus, they were used as a ‘guard ring’, and any events which triggered one or more off-source channels as well as an on-source channel would be rejected. This approach could have a software trigger added to it, which specified the percentage of the on-source signal that should be detected off-source.

In hindsight, this was too crude to make an appreciable difference to the signal to noise—but imaging was in its infancy at the time, and it was a good try.

2.3. Gamma-ray Sources (or Not)

I have already alluded to the NATO Advanced Research Workshop that was held in 1986. Since detecting a constant source was a considerable challenge without imaging, there was a great deal of concentration on variable sources. At that stage, nobody had detected an active galactic nucleus, so efforts were concentrated on variable objects in the Galaxy. This meant pulsars and binary systems containing neutron stars.

Back in 1986, the main source of excitement was Hercules X-1. An X-ray binary, this is known to contain a 1.24 s pulsar and to show cyclotron lines, indicative of a strong magnetic field. The first report of gamma-ray emission from Her X-1 came from Durham in 1984 [10]. At the 1986 meeting, the Durham, Whipple, and Haleakala groups all reported the detection of pulsed emission from the object [11–13]. An episode of emission in April 1984 was observed simultaneously with both the Dugway and Whipple telescopes, which independently measured the same pulse period [11]. Most of these reports translated into journal papers, and indeed there were many further reports in the 1980s [14–17], including a report from the Pachmarhi group of a strong burst of emission from the object [18]. Other binary systems came along too, sometimes without confirmation by more than one telescope, sometimes with: SMC X-1, Vela X-1, Cen X-3, LMC X-4, 4U0115+63,... it is quite a list [19]. The emission was generally episodic in nature and sometimes pulsed. There was also a clutch of upper limits.

The most intriguing object at the time was Cygnus X-3, first detected in gamma-rays in the 1970s with the Crimean Observatory telescopes [20,21]. This was followed by a confirmation from the Whipple Observatory [22], from the solar energy facility at Edwards Air Force Base [23] and from the Dugway telescopes [24]. All these observations seemed to show the object’s characteristic 4.8 h periodicity, although the exact time of the emission within the assumed orbit was not necessarily consistent. Most controversial were Durham’s claims of a 12.6 ms pulsar in the system, first seen in the data from the Dugway telescopes [25,26], and later from the Mark IV telescope operating on La Palma [27]. There were several apparent confirmations of this result, but on closer inspection, most did not stand up [28–30]. There was much discussion about the statistical approach taken, both for and against [31,32].

We are jumping ahead here, but none of these apparent signals were confirmed once it was possible to identify gamma-ray-induced images reliably. So what was going on? Was everyone slightly crazy? Maybe, but it seems to me more likely that this was a case of a series of marginally significant apparent signals reinforcing one another. Although in the end we did not learn very much from the observations, Hillas [2] pointed out that it was the Cygnus X-3 controversy in particular that kept ground-based gamma-ray astronomy alive and spurred on the development of Cherenkov telescopes and particle detector arrays. Cygnus X-3 is a known *Fermi*-LAT source, primarily detected in outburst [33],

and perhaps in the near future we will genuinely detect gamma-rays from the object with ground-based telescopes.

To go back to the aforementioned HERCULES detector, the intention was to add another 10 m class telescope to sit alongside the Whipple telescope and two high-resolution cameras (which then meant a pixel spacing of 0.25°) [7]. Hillas had already shown that images produced by gamma-ray showers could be distinguished from hadron-induced showers [34]. (In his modest way, Hillas never published this fundamentally important work in a refereed journal; with 233 citations⁴ and counting, it must be the most-cited cosmic ray conference paper in history.) The preamble to the description of HERCULES states:

Despite its obvious advantages, these ground-based techniques have not been developed to their full potential; the total investment in all such experiments on five continents since the early sixties amounts to only a few million dollars, a small percentage of the cost of GRO⁵, which included EGRET.), DUMAND⁶ or a major experiment in high energy physics.

Although the second telescope did not go quite to plan, with the publication of the Whipple team's ground-breaking detection of the Crab using the imaging atmospheric Cherenkov technique in 1989 [35], everything started to look different, and the prospects for more investment looked somewhat brighter. The imaging atmospheric Cherenkov telescope (IACT) had come of age.

3. The 1990s: Towards a Major Atmospheric Cherenkov Detector

It has been said for many years that there is the Crab, and then there is the rest of astronomy. The worry was that the rest of astronomy did not exist in very high-energy (VHE) gamma-rays; for a couple of years the catalogue seemed to consist of only the Crab Nebula. These worries were largely dispelled by the second object detected using the imaging technique: the blazar Markarian 421 [36]. This was particularly exciting, because it represented something new and completely unexpected—an active galaxy, no less, and one which was not detected strongly in the data from the EGRET gamma-ray telescope on board the Compton Gamma-Ray Observatory. This challenged the almost unspoken assumption that whatever was detected from the ground must also be bright at lower energies. The excitement was bolstered by the detection 4 years later of the second AGN with the Whipple telescope, Mrk 501 [37]—an object that was below EGRET's detectability threshold. Here was a whole new scientific area that the ground-based telescopes could exploit. It was convincing. It was time to build some bigger telescopes—but how, exactly?

The best way to go to give the sensitivity, angular resolution and energy resolution that would enable ground-based gamma-ray astronomy to move forwards was by no means clear. The options were discussed at length over a series of 6 international meetings entitled 'Towards a Major Atmospheric Cherenkov Detector', which ran from 1992 (in Paris) to 1999 (in Utah). (There was a seventh meeting in Paris some time later, in 2005.)

The starting position was that a single experiment was imminent, and a number of working groups were set up at the first meeting with this in mind: a science working group, a technical working group, and a simulations working group. These were reported back at the second meeting in Calgary in 1993. There were updates from the various groups around the world: Whipple had just completed a camera upgrade, which included a rotating camera head surrounded by scintillators (for recording the passage of local cosmic rays through the PMTs) on the 10 m telescope [38]; Durham had started stereoscopic imaging with the Mark 3A and 5A telescopes [39]; The Nootgedacht telescopes in South Africa were moving to a system of 6 'mini-telescopes' [40]; and the HEGRA⁷ telescopes destined for La Palma in the Canary Islands were in preparation [41]. There were also some rather heroic experiments described, including GASP⁸ at the South Pole [42]. Already by this stage, we can see the beginnings of discussions about silicon-based detectors, too [43].

However, at this point, the world was not ready for a single, major detector- or even collaboration. There was not, as yet, any consensus as to what 'the' detector would look like. As Weekes wrote in his postscript to the meeting:

...is it really obvious that the next major advances in ground-based gamma-ray astronomy will have to come with a single large “world” telescope? From my reading of the discussion at the workshop the answer was “no!”; one is bigger but more is better!

For the time being, it was on with more than one approach to the problem.

One option was to use an array of small mirrors spread across a large area. Measuring the arrival times of the Cherenkov light at each detector with sub-nanosecond resolution enabled very good directional information to be obtained, and wavefront sampling made it possible to improve the signal:noise, by exploiting the fact that the light front from a hadronic shower is much less uniform than that from gamma-rays. This approach was investigated by THEMISTOCLE in France and by PACT in India. THEMISTOCLE⁹ consisted of 18 small (0.8 m diameter) parabolic mirrors spread over an area of around $1.7 \times 10^5 \text{ m}^2$. This was used to detect the Crab Nebula, but as the mirrors were small, the threshold was high (3 TeV) and a 6.5σ detection of the Crab required 162 h of on-source observations [44]. PACT¹⁰, operated by the Tata Institute of Fundamental Research in India, did better. Although this also used small (0.9 m) mirrors, they were deployed in 25 clusters of 7, giving a lower threshold of 0.9 TeV. A test observation with half the array produced an 12σ detection of the Crab Nebula in 31 h, comparable to the Whipple telescope [45]. A very similar array located at Hanle in the Himalayas, the HAGAR¹¹ Observatory, has made a number of detections of AGN [46,47].

In 1991, a start was made on the construction of the HEGRA Cherenkov telescopes on La Palma. By 1998, this consisted of 5 telescopes of relatively modest area ($\sim 8.5 \text{ m}^2$), but importantly, all equipped with imaging cameras, eventually consisting of 271 pixels. This was a true stereoscopic Cherenkov telescope system, and clearly demonstrated the power of this technique, with its ability to locate gamma-rays to around 0.14° , and to reject around 90% of hadron-induced images [48]. The telescopes proved their worth with the detection of several new objects, including Cas A and M87 [49,50]; the final array ran successfully until 2002, when other projects began to take precedence.¹²

The Cherenkov array at Themis (CAT) was built on a similar timescale to the HEGRA telescopes, with operations starting in 1996 and ending in 2001 [51]. Although the telescope was small, with a 4.5 m diameter equivalent mirror, it was equipped with a 600-pixel camera. High-resolution spatial information was used to distinguish the gamma-ray events; by comparing the data to a detailed model it was possible to infer the position of the source on the sky, the impact point on the ground and the energy of the gamma-ray, even without stereoscopic information. This was also the first Cherenkov camera to contain integrated readout electronics, as is now the norm.

The Durham Mark 6 Telescope

Meanwhile, Durham looked at combining the imaging technique with a 3-mirror telescope system. Having constructed a small-scale prototype, the Mark 5A¹³, in 1992/3, the eventual result was the Durham Mark 6 telescope, shown in Figure 5 [52].



Figure 5. The Durham Mark 6 telescope in Narrabri, NSW, Australia. The telescope was around 20 m from end-to-end.

The Mark 6 telescope comprised 3 parabolic reflectors on a single mount, once again consisting of a honeycomb structure with an anodised aluminium skin, but this time formed into triangular sectors, so that a continuous reflective surface was created. These were too large for a vacuum chamber, but the relatively small sagitta of the mirrors, mostly in one direction, meant that it was possible simply to stretch the surface over the mould. However, we had probably reached the limit of the possible image quality with the anodised aluminium skin. Although malleable and durable, with excellent reflectance, there is a fundamental issue with the material that relates to the way it is manufactured. As a rolled material, there is an inherent directionality in the material and hence in the reflected light—the result had considerably diffuse reflectance in the direction in which the underlying aluminium had been rolled. Some batches were better than others, but the manufacturers did not know why. We seriously considered building aluminium-surface mirrors for H.E.S.S. at one point, but the company was not able to pursue any research into the reasons for the variations in quality without considerable financial input.

The camera at the focus of the central mirror represented Durham's first serious imaging camera (Figure 6), and consisted of 91 PMTs 2.5 cm in diameter with a surrounding ring consisting of 18, 5 cm diameter PMTs. The flanking dishes had simpler cameras at their foci, made of 19 close-packed hexagonal PMTs, which were 5.5 cm from flat-to-flat. These PMTs had come free of charge from a medical device manufacturer as part of huge job lot. Most of them were unused, either falling slightly out of specification, or having become parted from their test data (no manufacturer of medical equipment can afford not to have a full audit trail). This was very useful, as it enabled the best PMTs from the batch to be selected and used for telescopes. My job, as it had been in 1984, was to test the PMTs and construct the cameras—there was a lot of testing to be done, and I spent many hours sitting in our underground 'bunker' as it was known, in which the university's seismograph had been located at one time. This was very dark and prone to mice, but at least it was warm; the central heating pipes ran through it.

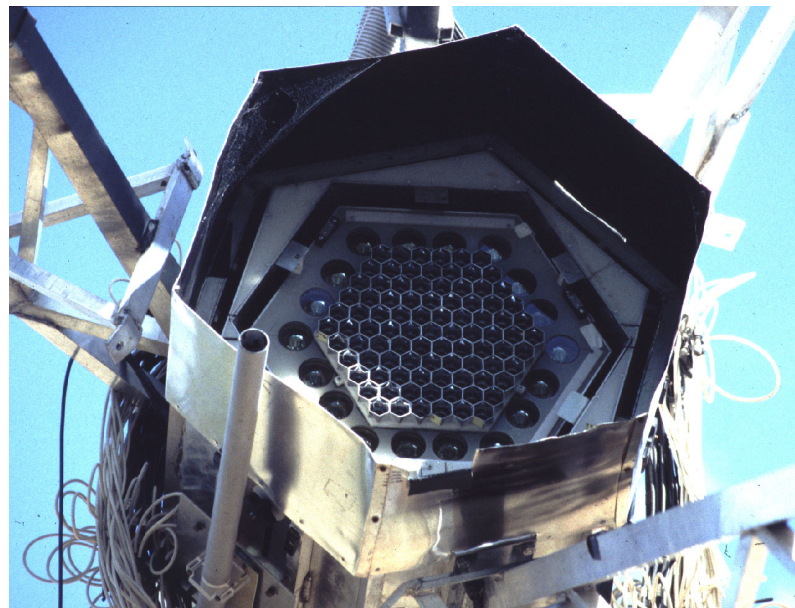


Figure 6. The Durham Mark 6 telescope's central camera.

The telescope was triggered via a coincidence between the central camera and corresponding PMTs in the lower-resolution left and right cameras. The camera trigger required that the left and right PMTs should be in the same region as at least 2 adjacent PMTs in the central camera. This trigger, devised by the ever-ingenious Lowry McComb, enabled the energy threshold to be lower than would usually be expected for a telescope situated not much above sea level, though I think not as low as the simulations suggested. Although there was no array trigger, once again, events from the Mark 6 could be correlated with those from the other telescopes on site, the 5A and 3A (a slightly upgraded Mark III), using the event timestamps.

Working in Australia was sometimes challenging. We had no onsite technical support, which meant that if you broke something, you were the one who would be fixing it. This made us all into careful and disciplined observers! The breakage which I personally hoped would not happen on my shift was to the main drive shaft to the gearboxes on the telescope drives. Occasionally these would snap, either due to general wear and tear or because a gust of wind had caught the telescope in question. Once the gearbox was off the telescope (no mean feat in itself), the top had to be prised off and the broken driveshaft removed from the drive trains. I can still remember the noise as the cogs in a 196:1 ratio gearbox moved—and the uncomfortable realisation that all of them needed to be put back into place.

Living with the wildlife in the bush was also interesting. We had various snakes, enormous spiders (which liked to live inside the electronics), echidnas, a large goanna, geckos in the house, some fabulous birds (not so fabulous when waking up those who had been observing all night), and many wallabies that were surprisingly easy to walk into at night. The local possum population was fascinated by the telescope mirrors, and we would often wake up in the day to find they had left paw marks on them. I suspect that anyone who has been observing at a remote site has similar stories to tell.

Some useful detections were made with the Mark 6 telescope, particularly PKS 2155-304 [53]. This held the IACT redshift record for couple of years, and of course, has turned out to provide a lot of science. There was some technical work too, and in particular Keith Orford's simulations of the effects of the geomagnetic field on Cherenkov images were borne out of the Mark 6 observations [54]. However, by 2000 the funds came to a halt and the time had come for us to pack up the telescopes in Australia. For ground-based gamma-ray astronomy in general, things were also starting to move on.

4. The 2000s: Opening the Window

4.1. Solar Farm Telescopes

It was—and indeed still is—very desirable to reduce the energy threshold of Cherenkov telescopes to a few 10s of GeV, in order to provide seamless energy coverage with satellite-based instruments. As so few Cherenkov photons are produced by low-energy showers, the main requirement is to have an exceptionally large mirror area. An attractive (and cheap) option to obtain the required area was to use solar power facilities. Here, large arrays of mirrors (heliostats) tracked the Sun, focusing sunlight onto a single target situated in a tower, thereby producing heat which was used to run a steam turbine. At night, of course, the heliostats were not in use, so they could be turned into large area Cherenkov telescopes by using them to track objects of interest. This idea was first proposed in 1982 [55], but was difficult to implement due to noise created by the overlapping heliostat images. However, a suitable arrangement of mirrors or Fresnel lenses could be used to improve the optics and focus the light onto PMTs [56]. There were four such adapted arrays that started operation in the 2000s. STACEE¹⁴ in New Mexico ultimately used 64 heliostats, each of area 37 m² [57]; CACTUS¹⁵ in California similarly used 64 heliostats, each of area ~40 m² [58]; CELESTE¹⁶ in France eventually used 53 mirrors of area 54 m² [59]; and GRAAL¹⁷ in Spain used 63 heliostats, each of area ~38 m² [60] (this last experiment used a slightly different optical configuration to the others).

Adapted solar farm telescopes made several detections of the Crab, Mrk 421 and Mrk 501 [61–64], as well as providing a number of upper limits, including of gamma-ray bursts [65]. Indeed, CELESTE was the first Cherenkov telescope to detect an object below 100 GeV [66]. (A nice review by Smith gives a summary of the various results [67]). However, the optical system required was tricky and did not provide a large field-of-view; it became clear that more conventional, although large, instruments would likely be better for the detection of gamma-rays below 100 GeV. CELESTE was dismantled in 2004, CACTUS ceased observations in 2005, STACEE stopped operations in 2007, and GRAAL shut down at about the same time.

4.2. IACT Arrays

By around 2000, it had become clear that an array of IACTs, all of 10-m class or larger and equipped with high-resolution cameras, would constitute that elusive major atmospheric Cherenkov detector. We are therefore now almost approaching the present day, and I do not propose to give a detailed summary of the next generation instruments H.E.S.S., MAGIC and VERITAS. There are a number of papers giving technical details of the telescopes [68–74], which are all in operation now. Their histories will be written by others in the future.

In addition to the arrays currently in operation, mention should also be made of the CANGAROO¹⁸ telescopes. The first CANGAROO telescope was 3.8 m in diameter and had originally been designed for lunar ranging. Successive upgrades culminated in a 256-pixel camera with a field-of-view of around 3° in 1995. This was followed by a 7 m telescope with a 512-pixel camera, and by 2003 there were 4 telescopes of 10 m diameter, each with a 427-pixel camera, dubbed CANGAROO-III [75,76]. The telescopes' mirrors were made of aluminium-coated carbon fibre-reinforced plastic. These were vulnerable to damage in the outdoor environment, and proved to be the Achilles heel of the telescopes. Nonetheless, CANGAROO reported detections of several objects, particularly Galactic objects such as RX J0852.0-4622 [77]. The last reported observations taken with the telescopes were in 2009.

Having closed down the Narrabri site in 2000, and with Ted Turver's retirement happening at about the same time, we in Durham joined the H.E.S.S. Collaboration. The 4 telescopes of H.E.S.S. I, each 12m in diameter and equipped with 960-pixel cameras (Figure 7), have of course provided a wealth of results over the years. We were part of H.E.S.S. for a lot of that time—until there was one of the intermittent UK funding crises, and our funds ran out. Working in a large collaboration was a new experience, since we had always run our telescopes on our own. It was a particular pleasure not to have to cover all the

observing sessions; it had been quite a strain for a group of around 10 people to cover all the dark moon periods over the years. When the telescopes were switched on, one of the first objects to be observed was PKS 2155-304 [78]. Michael Punch sent round an e-mail with the resulting detection and the wry comment that “this might interest our Durham colleagues”. It certainly did! I also remember Heinz Völk in a Collaboration Board meeting in (I guess) 2004 commenting that we would have to manage the expectations of our PhD students—there would not be “an object each” as he put it. Shortly afterwards, the first Galactic plane scan results arrived [79], and I think it is fair to say that, just this once, Heinz was proved wrong.

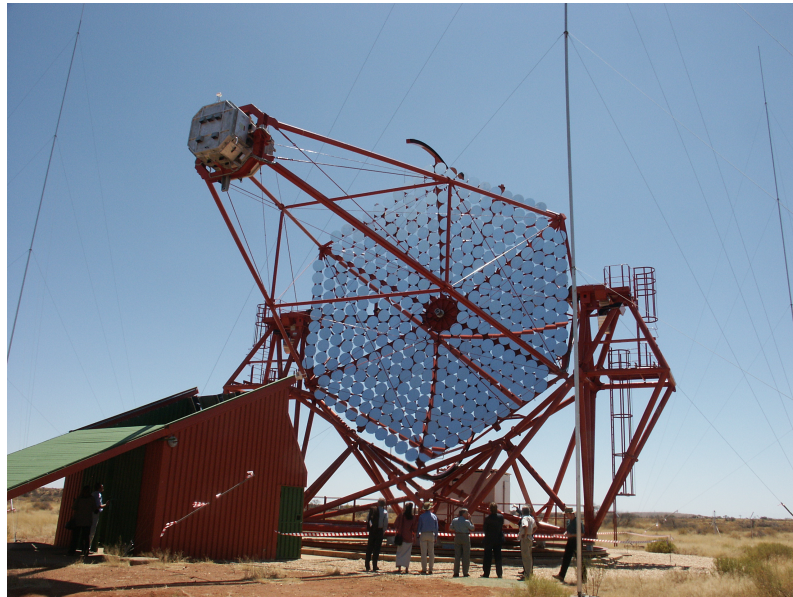


Figure 7. One of the H.E.S.S. I telescopes at the array’s inauguration in 2004.

The successes of these third generation telescopes have resulted in a considerable catalogue of objects; indeed, there are now considerably more classes of object detected than there were objects back in 2000. The excellent TeVCat¹⁹, maintained by Deirdre Horan and Scott Wakely (to whom the whole field owes a debt of gratitude), now lists 243 sources, a figure that nobody would have believed possible back in 1984 when I started. There had been a joke amongst gamma-ray astronomers—I am not sure where it originated—that one photon constituted a detection, two was a spectrum, and three was variability. Now, gamma-ray telescopes provided spectra and variability detection in abundance, and even images, heralded by the H.E.S.S. detection of RXJ1713-3946 [80].

5. 2010 to the Present: May the Fourth Be with You

Even in 2000, when most telescope arrays were in the final stages of design or the early stages of construction, there were ideas for the 4th generation of Cherenkov telescopes. One of these was 5@5, a proposal to build an array of 5 telescopes at 5 km above sea level, which would give an energy threshold of 5 GeV [81]. This was all part of a lively debate regarding whether it was better to go to low energies to meet—and compete—with satellite-based instruments or to do what satellites could not, and go to higher energy. The answer, of course, was to do both, and so the Cherenkov telescope array (CTA) concept began to emerge, with its large, medium and small telescopes covering the range from a few 10 s of GeV to 100 s of TeV. No doubt there will be much more detail about CTA in this volume, and there are two comprehensive guides to CTA and its scientific objectives available [82,83], so I will confine myself (once again) to a few observations from my perspective.

The arrival of Jim Hinton in the UK in 2006 gave the field a boost, and a number of groups had begun to coalesce around CTA. There were a few false starts, but by 2012, we

had a small amount of funding to get us going, and now there are 5 groups in the UK forming a core CTA team, from Armagh Observatory & Planetarium, and the universities of Leicester, Liverpool, Oxford and Durham²⁰. In 2021, we held a 2-day meeting about CTA in the UK, which over 90 scientists attended. It was very different from that meeting in 1986. We are no longer primarily discussing what may or may not actually be producing gamma-rays; the scientific implications are taking centre-stage. There is interest from AGN modellers, cosmologists, radio astronomers and particle physicists. Ground-based gamma-ray astronomy has taken the place of one of the many tools which we use to try to understand the Universe.

I have avoided discussing the particle detector arrays, largely because they are not something with which I have been involved up until recently. However, the results from HAWC [84] have shown us the value of such arrays with their ability to view the entire overhead sky day and night, come rain or shine. The move to build a large particle detector array in the southern hemisphere in the shape of the Southern Wide-field Gamma-ray Observatory (SWGGO) will be an important complement to CTA [85], but importantly, LHAASO (Large High Altitude Air Shower Observatory) has revealed more, and more energetic, objects than we might have expected, emphasising the importance of such instruments in their own right [86]. Couple these with the neutrino detectors and gravitational wave detectors and CTA, and it is easy to see that there's a very exciting time ahead in astroparticle physics. It's almost enough to make me wish I was starting again. Almost...

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Acknowledgments: I have encountered so many people over the 30-odd years that I probably shouldn't pick out any names for fear of offending anyone by their omission. However, I am going to venture to mention a few of the people from the early days in Durham who were pivotal to the group's work, but perhaps did not always hit the headlines. Lowry McComb was not only the electronics design mastermind for our telescopes but also a simulations and physics guru, and taught me how to solder (at least passably); our technical staff Sue Hilton, Ken Tindale and Peter Cottle made up cables, welded aluminium, built consoles, kept the Observatory van going and did countless other things over the years; John Dowthwaite taught me a great deal about statistics, as well as the rules of cricket; Ian Kirkman was an exceptional data analyst who taught me how to analyse gamma-ray data; and finally, Steve Rayner's careful and meticulous approach to data-taking and ability to sing Flanders and Swann songs made many an observing trip a success. I hope that I have not forgotten anyone and equally hope that those whom I have will forgive me. Thanks are also due to the current members of the group in Durham for putting up with my muttering about this review (and indeed for putting up with me in general): Atreya Acharyya, Anthony Brown, Max Harvey, Sheridan Lloyd, Abi Peake, Alberto Rosales de Leon, Cameron Rulten, and Patrick Stowell. Finally, I would like to thank Ulisses Barres de Almeida and Michele Doro for asking me to write this review. It has been instructive to look back; I hope the result is what you wanted!

Conflicts of Interest: The author declares no conflict of interest.

Notes

- ¹ The Whipple Telescope, operated at Mount Hopkins in Arizona.
- ² High Energy Radiation Cameras Using Light Emitting Showers—this field has never been short of acronyms.
- ³ Available online: <https://alanod.com>, accessed on 30 August 2021.
- ⁴ As of 2 September 2021.
- ⁵ The Compton Gamma-Ray Observatory.
- ⁶ Deep Underwater Muon and Neutrino Detector array. Rather similar to KM3NeT in concept, it was cancelled in 1995, just before full deployment.
- ⁷ High-Energy Gamma-Ray Astronomy.
- ⁸ Gamma-ray Astronomy at the South Pole.
- ⁹ A rather wonderful acronym—Tracking High Energy Muons In Showers Triggered On Cerenkov Light Emission.

- 10 Pachmarhi array of Cherenkov telescopes.
- 11 High-Altitude Gamma Ray.
- 12 Durham also ran a telescope (the Mark IV) briefly on La Palma and I remember visiting the HEGRA Cherenkov telescopes. We were impressed that all the cables were cut neatly to length and no longer. This gave the impression that a need for fault-checking with an oscilloscope was not expected.
- 13 With the advent of imaging, the Durham telescope numbers changed from Roman to Arabic. I do not think that this was intentional!
- 14 the Solar Tower Atmospheric Cherenkov Effect Experiment.
- 15 Converted Atmospheric Cherenkov Telescope Using Solar-2.
- 16 an acronym that seems to be shrouded in mystery.
- 17 Gamma Ray Astronomy at ALmeria.
- 18 Another magnificent acronym—Collaboration between Australia and Nippon (Japan) for a GAMMA Ray Observatory in the Outback.
- 19 Available online: <http://tevcat.uchicago.edu/>, accessed on 3 September 2021.
- 20 Sadly, the University of Leeds group, which had done so much for ground-based gamma-ray astronomy and astroparticle physics in general, disbanded in around 2013.

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